# DECOMPRESSION PROCEDURES FOR THE SAFE ASCENT OF AEROSPACE PERSONNEL FROM GROUND LEVEL TO ALTITUDE

Contract NAS 9-6978



Final Report

to:

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Manned Spacecraft Center
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## APPENDIX

## I. INTRODUCTION AND SUMMARY

Under contract NAS 9-6978 we have subjected 388 manned altitude flight records to a theoretical analysis to determine those parameters which are important in the construction of decompression tables for aerospace personnel. The flight records analyzed were generated by the U. S. Navy Air Crew Equipment Laboratory, Philadelphia, and the U. S. Air Force School of Aerospace Medicine, San Antonio, Texas.

The partial pressure of inert gas dissolved in several hypothetical body compartments was computed and, together with all other available pertinent flight and subject information stored on magnetic tape. This information was then correlated with the incidence of decompression sickness. For flights in which nitrogen was the only inert gas present, risk predictions could be developed for the target pressure range of 150-200 mm Hg. Some risk predictions (limited by the number of available flight records) could also be derived for target pressures of 250-300 mm Hg and 350-400 mm Hg. No predictions of the risk of decompression sickness could be developed for flights in which both helium and nitrogen were present in the body tissues.

The analyses performed under the present contract justify the expectations that the approach used by us is capable of producing decompression procedures for the safe ascent of aerospace personnel from ground level to altitude. To accomplish this objective it is necessary to analyze additional altitude flights to a wide range of target pressures with emphasis on high-risk flight profiles. In this manner it will be possible to refine and strengthen the results of the present analysis. Additional analyses will, in particular, aid in the development of risk predictions that take into account the duration of the altitude exposure and that reflect the severity of decompression sickness which may be encountered.

## II. EVALUATION OF FLIGHT PROFILES

### A. Tonawanda II Model of Inert Gas Transport

A simple mathematical model of inert gas transport (Schreiner, 1968) has found extensive application in our Laboratory for the computation of successful decompression schedules for open sea dives to depths as great as 700 feet. This model, designated "Tonawanda II", perceives of inert gas transport as being limited by tissue perfusion (Jones, 1950). It also assumes that the probability of an inert gas remaining in supersaturated solution in the tissues is dependent on the magnitude of this supersaturation relative to the prevailing ambient pressure.

In Table I are presented the symbols which we use to denote the factors that enter into the mathematical relationships which we have developed to describe perfusion-limited transport of inert gases. In Figure 1 is shown a schematic overview of this transport. Assuming complete equilibration of inert gas partial pressure between blood and alveoli, the quantity (volume, STP) of inert gas which a unit volume of blood carries away from the lungs per unit of time is given by $V_{IG_a} = \dot{Q}\alpha_{blood} \cdot P$. By the same token, if inert gas transport to and from the tissues is limited by perfusion, then one must assume equilibration of dissolved inert gas partial pressure between capillary blood and tissue. Hence the volume (STP) of inert gas carried away from a given tissue per unit of time by a unit volume of blood is given by $V_{IG_v} = \dot{Q}\alpha_{blood} \cdot \pi$. Clearly, then, the change per unit of time in volume (STP) of inert gas dissolved in a unit volume of tissue is equal to the difference between the quantity of inert gas in the arterial blood entering the tissue, and the quantity of inert gas in the venous blood leaving the tissue, i.e.

$$-\Delta V_{IG_t} = V_{IG_v} - V_{IG_a} \tag{1}$$

Table I

## Explanation of Symbols Used

| | | |
|---|---|---|
| $\pi$ | = | Partial Pressure of Inert Gas Dissolved in the Tissue |
| $t$ | = | Time |
| $k$ | = | Specific Time Constant of Gas Transport |
| $t_{\frac{1}{2}}$ | = | Half-time of Gas Transport = $\ln 2/k$ |
| $P$ | = | Alveolar Partial Pressure of Inert Gas |
| $c$ | = | (constant) Rate of Increase or Decrease of P with Time |
| $Q$ | = | Rate of Tissue Perfusion (Volume/Time Unit/Volume) |
| $\alpha$ | = | Gas Solubility |

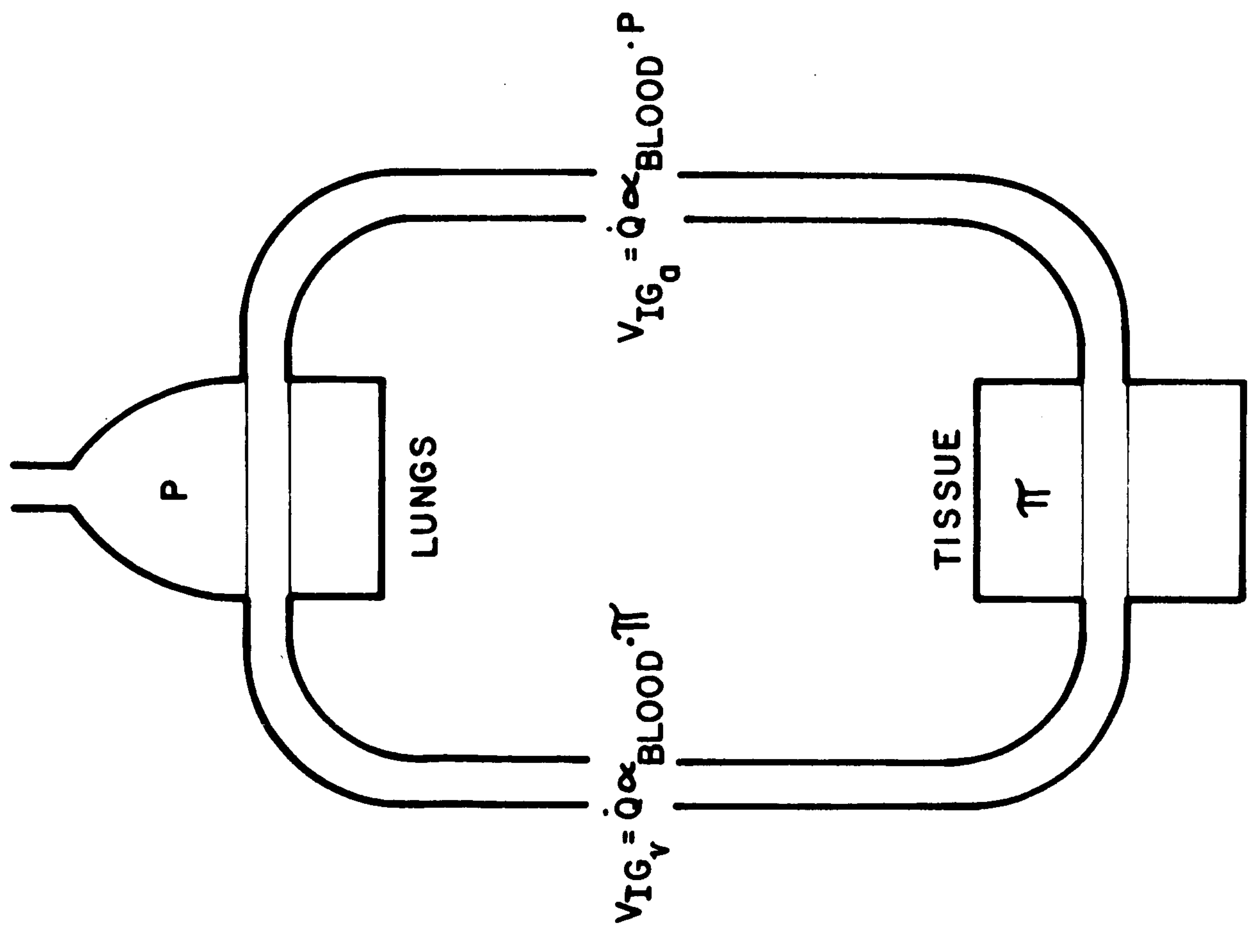
Figure 1

$$-\frac{dV_{IG_t}}{dt} = V_{IG_v} - V_{IG_a}$$

$$-\frac{d\pi}{dt}\alpha_{TISSUE} = \dot{Q}\alpha_{BLOOD}(\pi - P)$$

$$\frac{d\pi}{dt} = \dot{Q}\frac{\alpha BLOOD}{\alpha TISSUE}(P-\pi)$$

$$k = \dot{Q}\frac{\alpha BLOOD}{\alpha TISSUE}$$




Schematic Presentation of Perfusion-Limited Inert Gas Transport

Since the volume of inert gas dissolved in a given tissue is given by

$$V_{IG_t} = \alpha_{tissue} \cdot \pi , \qquad (2)$$

equation (1) may be written as

$$-\frac{d\pi}{dt} \alpha_{tissue} = \dot{Q} \alpha_{blood} \cdot \pi - \dot{Q} \alpha_{blood} \cdot P \qquad (3)$$

which may be rearranged to yield:

$$\frac{d\pi}{dt} = \dot{Q} \frac{\alpha_{blood}}{\alpha_{tissue}} (P - \pi) \qquad (4)$$

which represents the basic inert gas transport equation. This differential equation states that the rate of change of inert gas partial pressure dissolved in a given tissue is at all times proportional to the difference betweeen alveolar and tissue inert gas partial pressure. The proportionality constant $\dot{Q} \frac{\alpha_{blood}}{\alpha_{tissue}}$ represents the specific time constant k of inert gas transport. We shall come back to the physiological importance of this identity later on.

Figure 2 shows the inert gas transport equation and its general solution. To solve this equation numerically, it is necessary to define the functional relationship between the alveolar inert gas partial pressure P and time. If the rate of change of P with time is constant (including zero), a numerical solution may be simply obtained. With the aid of the gas transport equation, and a knowledge of the initial values of P and $\pi$ it is therefore possible to compute the inert gas partial pressure $\pi$ at any time during linear or step-wise ascent or descent for any tissue for which the value of k can be determined or deduced from the rate of its perfusion and from its fat content. This physiological interpretation of the value of k is illustrated in Table II. Assuming tissue to consist of a

Figure 2

<u>GAS TRANSPORT EQUATION:</u>

$$\frac{d\pi}{dt} = k\,(P-\pi)$$

<u>GENERAL SOLUTION:</u>

$$\pi = e^{-\int k\,dt}\left[\int P e^{\int k\,dt}\,dt\right] + C_1 e^{-\int k\,dt}$$

<u>SPECIAL SOLUTION FOR $\frac{dP}{dt} = C$:</u>

$$\pi = P_0 + C\left(t - \frac{1}{k}\right) - \left(P_0 - \pi_0 - \frac{C}{k}\right) e^{-kt}$$

$$k = \dot{Q}\,\frac{\alpha\ \text{BLOOD}}{\alpha\ \text{TISSUE}}$$

Table II

**Perfusion-Limited Inert Gas Transport**

$$k = \dot{Q}\,\frac{\alpha \text{ blood}}{\alpha \text{ tissue}} \quad ; \quad t_{\frac{1}{2}} = \frac{\ln 2}{k}$$

$\alpha$ blood = $\alpha$ water

$\alpha$ tissue = $(1-x)\ \alpha$ water + $x \cdot \alpha$ fat

$$\frac{\alpha \text{ blood}}{\alpha \text{ tissue}} = \frac{1}{1 + x\,([\alpha \text{ fat}/\alpha \text{ water}] - 1)}$$

$\frac{\alpha \text{ fat}}{\alpha \text{ water}}$ : Helium: 1.70 Nitrogen: 5.10

| | | | | |
|---|---|---|---|---|
| Blood Flow $\dot{Q}$, $min^{-1}$ | 0.0085 | 0.0085 | 0.0085 | 0.0085 |
| Fat Fraction x of Tissue | 0 | 0.3 | 0.7 | 1.0 |
| $t_{\frac{1}{2}}$ He, min. | 81 | 99 | 122 | 139 |
| $t_{\frac{1}{2}}$ $N_2$, min. | 81 | 182 | 315 | 416 |

variable mixture of fat and water, and further assuming that the solubility of inert gases in blood is equal to that in water, the specific time constant k (or half-time of inert gas transport, $t\frac{1}{2}$) for a particular inert gas, can be derived from the relative solubility of an inert gas in fat and water, and from the fat fraction x of a given tissue, as long as the rate of perfusion $\dot{Q}$ is known. Equation (4) can therefore be rewritten as follows:

$$\frac{d\pi}{dt} = \dot{Q} \quad \frac{1}{1 + x\left([\alpha_{fat} / \alpha_{water}] - 1\right)} \quad (P - \pi) = k\,(P - \pi). \qquad (5)$$

Certain limits can be set for the rate of perfusion and the fat fraction of a tissue. The distribution coefficient of an inert gas between fat and water is generally known with precision. We have deliberately assumed that the rate of perfusion in man ranges from a minimum of 0.0085 $min^{-1}$ to a maximum which is greater than 0.3 $min^{-1}$, and that the fat fraction x of human tissue may range from 0 to 1.0. Within these limits it is possible to conceive of an infinite number of combinations of $\dot{Q}$ and x , giving rise to an infinite number of values of k for a given inert gas. For the purpose of following the time course of inert gas partial pressures dissolved in various gas exchange units of the human body it is sufficient to limit attention to the combination of a few representative values of $\dot{Q}$ and x . The Tonawanda II Model of inert gas transport employs 15 such combinations as outlined in Table III.

Since ascent to altitude is tantamount to saturation decompression after a "dive" to 760 mm Hg with an extended "bottom time" at this pressure, safe ascent from ground level to altitude is limited by the speed with which the slowest tissue units of the body (mathematically represented as the compartment with the smallest specific time constant of inert gas transport) is able to lose gas during (and after) ascent. In our model, compartment 15 has the smallest specific time constant of inert gas transport and is therefore considered to be ascent-limiting during decompression from saturation dives. As shown in Table III compartment 15 has a half-time of 139 minutes for helium transport, and of 416 minutes for nitrogen transport, since

Table III

Information Describing Inert Gas Exchange Compartments
Employed in the Computer Evaluation
of Decompression Profiles

| Compartment No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\dot{Q}$ , $min^{-1}$ | 0.3 | 0.3 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.03 | 0.03 | 0.03 | 0.03 | 0.0085 | 0.0085 | 0.0085 | 0.0085 |
| Fat Content of Tissue, per cent | 30 | 70 | 100 | 0 | 30 | 70 | 100 | 0 | 30 | 70 | 100 | 0 | 30 | 70 | 100 |
| $t_{1/2}$ - He, min. | 3 | 3 | 4 | 7 | 8 | 10 | 12 | 23 | 28 | 34 | 39 | 81 | 99 | 122 | 139 |
| $t_{1/2}$ - $N_2$ , min. | 5 | 9 | 12 | 7 | 15 | 27 | 35 | 23 | 52 | 89 | 118 | 81 | 182 | 315 | 416 |

$$t_{\frac{1}{2}} = \frac{\ln 2}{k} = \frac{0.693}{0.0085} \cdot \frac{\alpha_{fat}}{\alpha_{water}} = 81.5 \frac{\alpha_{fat}}{\alpha_{water}} \quad . \tag{6}$$

The alveolar partial pressure of nitrogen is related to the inspired fraction of oxygen, $F_{IO_2}$, inspired partial pressure of nitrogen, $P_{I_{N_2}}$, respiratory quotient, R, and alveolar $P_{CO_2}$ by the alveolar nitrogen equation (Rahn and Fenn, 1955)

$$P_{A_{N_2}} = \frac{(1-F_{IO_2})\, P_{A_{CO_2}}\, (1-R)}{R} + P_{I_{N_2}} \quad . \tag{7}$$

The equation may be rewritten as

$$P_{A_{N_2}} = F_{I_{N_2}} \left( \frac{P_{A_{CO_2}}\,(1-R)}{R} + B - 47 \right) , \tag{8}$$

where B represents the barometric pressure in mm Hg. By assuming standard values of R (0.8) and of alveolar $P_{CO_2}$ (40 mm Hg), equation (8) reduces to

$$P_{A_{N_2}} = F_{I_{N_2}} (B-37) \ . \tag{9}$$

Assuming that the alveolar nitrogen equation can be applied to inert gases in general ($F_{I_{N_2}} = F_{I_{IG}}$), combination of equations (5) and (9) yields the expression

$$\frac{d\pi}{dt} = \dot{Q} \; \frac{1}{1 + x\left([\alpha_{fat}/\alpha_{water}] - 1\right)} \left(F_{I_{IG}} [B-37] - \pi\right) \tag{10}$$

which was used to compute inert gas partial pressures in the 15 gas exchange compartments of the Tonawanda II model throughout each of 388 altitude flights analyzed under Contract NAS 9-6978.

For compartment 15 ($\dot{Q}$ = 0.0085 min$^{-1}$, x = 1.0), equation (10) reduces to

$$\frac{d\pi}{dt} = 0.0085 \frac{\alpha_{water}}{\alpha_{fat}} (F_{I_{IG}} [B-37] - \pi). \qquad (11)$$

B. Computational Approach

A data record format for the treatment of the information supplied by the flight records available for analysis was selected with the view of developing a decompression information system of sufficient capacity and flexibility to meet not only the requirements of this contract but also to meet all foreseeable requirements of the National Aeronautics and Space Administration for the processing of decompression data. This included both a coding format to insure the uniform handling of the data received and their transcription unto data sheets, and a library record format for the comprehensive representation of the results of our analyses on magnetic tape.

The coding format consists of the following elements:

(a) Each subject is identified uniquely by 5 digits with the first two digits identifying the geographic location where the data was generated, and the last three digits identifying the individual subject.

(b) The physical characteristics of each subject are coded and placed in external file. Age, weight, and height are the only physical characteristics reported for all subjects whose records were available to us.

(c) Each flight is identified uniquely by 5 digits.

(d) The date of each flight is identified by 6 digits (day-month-year).

(e) The unit of time is one minute, the unit of pressure is one mm Hg.

(f) The degree of activity of each subject during each altitude decompression run is coded as follows:

-1 no information
0 no activity
1 activity but no exercise
2 light exercise
3 medium exercise
4 heavy exercise

(g) The severity of physiological signs and symptoms is coded as follows:

-1 no information
0 no pain or discomfort
1 forehead pain and other types of discomfort and/or pain not necessarily associated with decompression sickness
2 paresthesia, vasomotor abnormalities, skin rash, blurred vision, and similar manifestations likely to be associated with decompression sickness
3 slight discomfort or pain
4 definite pain, steady and moderate
5 severe pain

The School of Aerospace Medicine employs a numerical grading system to describe the severity of the symptoms of decompression sickness; the flight records generated by the Air Crew Equipment Laboratory contain entries of the subject's own characteristics of his symptoms. It became therefore necessary to reconcile these two systems. This was done by introducing the grading method outlined above.

(h) The location of physiological signs and symptoms on or in the human body is identified by four digits. A maximum of four different locations may be identified simultaneously.

The library record format specifies that the following information is recorded at each pressure/time discontinuity and at each incident of decompression sickness with a code of 1, 2, 3, 4, or 5:

Location
Subject Number
Date
Flight Number
Time
Total Pressure
Calculated Alveolar Partial Pressure of Each Inert Gas Breathed

Activity
Physiological Signs and Symptoms
Location of Physiological Signs and Symptoms (Up to Four Locations)

For each of the 15 inert gas transport compartments of the Tonawanda II model and for each inert gas the following calculated information is recorded:

Tissue Partial Pressure of Dissolved Inert Gas (Pi Value)
Partial Pressure Minus Pi Value
Pi Value Minus Total Pressure

For each of 15 compartments, the following calculated information is recorded:

Sum of Pi Values
Sum of Partial Pressures Minus Sum of Pi Values
Sum of Pi Values Minus Total Pressure
Sum of Pi Values Divided by Total Pressure.

Some comment concerning the significance of this information is in order. "Partial Pressure Minus Pi Value" represents the 'driving force' of exchange of a particular inert gas. If this quantity is negative, gas is leaving the body; if it is positive, inert gas is being taken up. "Sum of Pi Values" denotes the total pressure exerted by two or more inert gases dissolved in the tissues at the same time. "Sum of Partial Pressures Minus Sum of Pi Values" represents the overall (net) driving force of the simultaneous transport of two or more inert gases. "Pi Value Minus Total Pressure" represents the relative saturation of a particular compartment with all inert gases. If this value is positive, supersaturation exists and decompression sickness may occur. Relative inert gas saturation may also be expressed as "Sum of Pi Values Divided by Total Pressure, " also known as Haldane Ratio. When expressed in this manner, supersaturation exists if this ratio is greater than unity.

A proprietary digital computer program was used to calculate partial pressures of inert gases dissolved in the 15 compartments of the

Tonawanda II model according to equation (10), and to transcribe the results of these calculations onto magnetic tape. At the beginning of each flight, all compartments were considered to be equilibrated with nitrogen at a partial pressure of 0.79 times the prevailing barometric pressure. All barometric data needed to evaluate the altitude decompression records originated by the Air Crew Equipment Laboratory was obtained from the U. S. Weather Bureau in Philadelphia. The pressure values obtained were rounded off to the nearest even mm Hg.

The input data for the calculations performed were total pressure, time, and composition of the breathing gas mixture. When oxygen alone or in combination with helium was breathed, it was assumed that administration of these gases took place by mask in an air environment at ground level or at altitude. In such instances, an inboard nitrogen leakage was assumed to produce a nitrogen level in the inspired gas mixture equal to 2 per cent of the total pressure.

Additional proprietary computer programs used in the course of the present study include:

a program to print out any specified section of a result tape;

a program to place the physical characteristics of each subject on tape;

a program to perform correlative analyses of data on "result" tapes;

a program to draw plots of the time course of inert gas partial pressures in selected inert gas transport compartments;

a program to draw plots of maximum Haldane Ratios sustained in all flights against weight or age of the subject with each plotted point indicating decompression success or failure.

## III. RESULTS AND DISCUSSION

### A. Test of the Tonawanda II Model

The following computations were carried out in order to determine if the Tonawanda II model of inert gas transport is capable of correctly predicting the incidence of decompression sickness in altitude flight profiles on the basis of calculated inert gas tensions in the ascent-limiting compartment.

Using equation (11), the time course of the sum of inert gas partial pressures in compartment 15 was calculated in 12 simulated MOL profiles flown in altitude chambers at the USAF School of Aerospace Medicine (McIver, Allen, Beard, and Bancroft, 1967). For each MOL profile, the maximum Haldane Ratio (sum of Pi values divided by total pressure, $\Sigma\pi/B$) sustained was recorded, and all profiles ranked in order of increasing magnitude and frequency of occurrence of this maximum Haldane Ratio. For example, if a particular maximum relative supersaturation was encountered three times in a given MOL profile, we would judge this flight profile to be more prone to result in decompression sickness than if the subject had been exposed to this high relative supersaturation only once or twice.

Where more than one profile fell into one of these gross and admittedly arbitrary categories, we subclassified these profiles further by noting differences in the second highest value of $\Sigma\pi/B$ associated with a given profile (Table IV).

On this basis we were able to rank the 12 simulated MOL profiles in terms of the relative severity of the episodes of supersaturation associated with each. We then compared this ranking with the actual bends experience associated with the 12 simulated MOL profiles analyzed (Table V). This comparison is presented graphically in Figure 3. Inspection of this figure shows that except for profiles 2B and 2C the Tonawanda II model predicted the relative hazards of decompression sickness for all

Table IV

Classification of Twelve Simulated MOL Profiles

| Category | Range of Peak Values of $\Sigma\pi/B$ | Subclassification Values of $\Sigma\pi/B$ | MOL Profile No. |
|---|---|---|---|
| I | < 2.0 | 1.40<br>1.51<br>1.63<br>1.70 | 12<br>10<br>11<br>8 |
| II | 2.03 - 2.08 (once) | | 9 |
| III | 2.03 - 2.08 (twice) | 1.20<br>1.36<br>1.37<br>1.67 | 3<br>4<br>7<br>5 |
| IV | 2.01 - 2.08 (three times) | | 6 |
| V | 2.37 - 2.65 (three times) | | 1 |
| VI | 2.37 - 2.65 (three times)<br>2.0 - 2.04 (once) | | 2 |

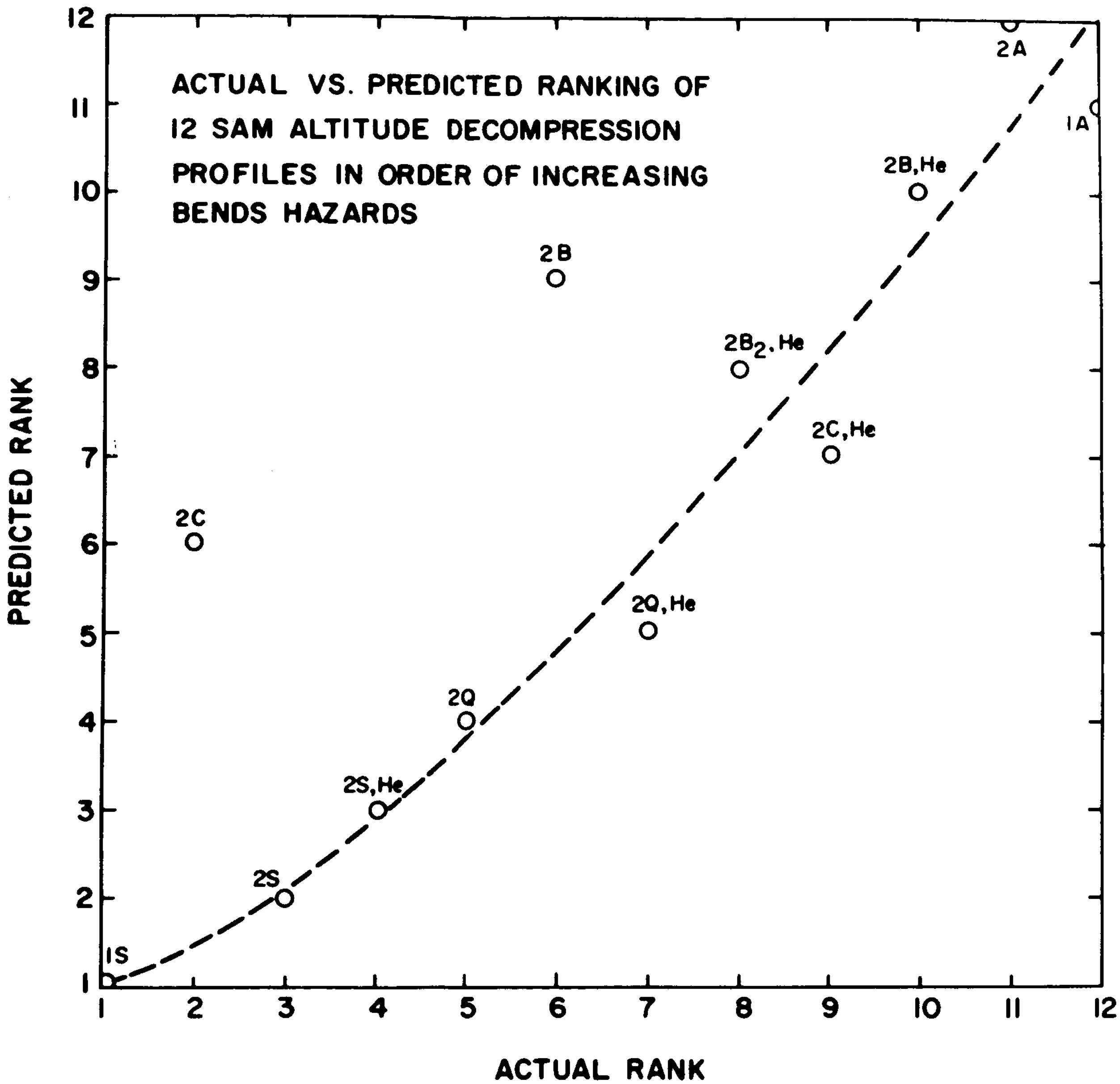
Table V

**Computer Prediction Vs. Actual Ranking of Twelve Simulated MOL Decompression Profiles* in Order of Increasing Incidence of Decompression Sickness**

| Profile Designation | | Ratio of Reported | Per Cent Incidence of | Rank | |
|---|---|---|---|---|---|
| SAM | Linde | Bends to Subjects | Bends | Predicted | Actual |
| 1S | 12 | 1/28 | 4 | 1 | 1 |
| 2C | 3 | 2/30 | 7 | 6 | 2 |
| 2S | 10 | 3/36 | 8 | 2 | 3 |
| 2S, He | 11 | 4/35 | 11 | 3 | 4 |
| 2Q | 8 | 9/38 | 24 | 4 | 5 |
| 2B | 5 | 12/50 | 24 | 9 | 6 |
| 2Q, He | 9 | 11/39 | 28 | 5 | 7 |
| $2B_2$, He | 7 | 12/32 | 37 | 8 | 8 |
| 2C, He | 4 | 5/10 | 50 | 7 | 9 |
| 2B, He | 6 | 19/38 | 50 | 10 | 10 |
| 2A | 2 | 28/31 | 90 | 12 | 11 |
| 1A | 1 | 25/19-21 | 119 | 11 | 12 |

*Reference: Dr. R. G. McIver, USAF School of Aerospace Medicine, San Antonio, Texas.

Figure 3


ACTUAL VS. PREDICTED RANKING OF
12 SAM ALTITUDE DECOMPRESSION
PROFILES IN ORDER OF INCREASING
BENDS HAZARDS
PREDICTED RANK
ACTUAL RANK
1S
2S
2S,He
2Q
2Q,He
2C
2B
$2B_2$,He
2C,He
2B,He
2A
1A
1
2
3
4
5
6
7
8
9
10
11
12

other profiles with remarkable accuracy. The position of flights 2B and 2C in Figure 3 is significant, because for both flights the model erred on the conservative side, by predicting a greater relative bends hazard than was actually encountered.

This surprisingly accurate prediction of the relative decompression hazard associated with each of the 12 flight profiles analyzed is particularly remarkable since the ranking methods used were admittedly crude. For example, neither the nature of the inert gases ( helium and/or nitrogen) dissolved in the tissues, nor the total pressure at which supersaturation was sustained, nor the rate of decay of this supersaturation was taken into consideration in arriving at the predicted ranking. Also, we did not take into account the point of occurrence nor the severity of the reported symptoms, but merely computed the ratio of the number of reported incidences of decompression sickness to the number of subjects flying each profile to arrive at the ranking of actual decompression experience. Finally, no attempt was made to account for changes in the value of Q due to exercise or the breathing of oxygen.

On the basis of these results, we proceeded to analyze a total of 388 individual altitude flight profiles in a similar manner in order to derive ascent-limiting conditions of dissolved tissue inert gas pressure for the development of safe decompression procedures for the ascent of aerospace personnel to altitude.

B. Analyses of 388 Flight Records

A total of 429 altitude decompression records were received from Manned Spacecraft Center for analysis under this contract. These records had been obtained in 72 altitude decompression chamber experiments performed on 37 subjects by the U. S. Navy Air Crew Equipment Laboratory at Philadelphia and in 49 altitude decompression chamber experiments performed on 17 subjects by the USAF school of Aerospace Medicine at Brooks Air Force Base. Twenty-five of these records were found to lack essential information such as date or subject information. This information could not be retrieved by the Air Crew Equipment Laboratory and the flights affected were dropped from consideration. The remaining 404 records were coded and the information entered on punch cards. On final inspection, 16 of these 404 records were found to be sufficiently deficient in information content to merit their elimination; the remaining 388 flights were processed, the results transcribed onto magnetic tape, and subjected to 11 correlative and 22 graphic computer analyses.

The computer analyses* performed on the processed 388 flight records represent a process of evolutionary refinement. The first two analyses performed attempted to correlate decompression success with the Haldane Ratios sustained in compartment 15 at the various pressure/time discontinuities of each flight, without regard to the nature of the inert gas dissolved in the tissues. This did not produce conclusive results. This approach was refined in Analysis No. 4 where only the highest Haldane Ratio sustained in each flight was used as the basis for correlation with the incidence of decompression sickness. This is the approach which we used in the successful evaluation of the 12 MOL flight profiles to test the Tonawanda II model, and it proved to be fruitful again: the incidence of decompression sickness increased with increasing maximum Haldane Ratio, except that an abnormally low rate of incidence of decompression sickness in the Haldane Ratio range of 2.21 - 2.40 was noted. Analysis No. 9 reviewed the flights which generated this data. It developed that these flights were generated at the Air Crew Equipment Laboratory, Philadelphia, and were flights in which helium was not breathed. Considering the rapidity of onset of bends symptoms in flights in which helium is breathed (as shown by Analysis No. 8), it is logical to ascribe to sample bias the low incidence of decompression sickness in the Haldane Ratio range of 2.21 - 2.40.

Diving experience has shown that permissible supersaturation, if expressed as a ratio of dissolved gas tension to total pressure, varies with depth. Since the flights analyzed in the present study varied considerably in the minimum total pressure attained, it was felt to be

*The rationale of these analyses and their over-all results are presented in Appendix II to this report.

appropriate to base further analyses on dissolved inert gas tensions calculated for compartment 15 within selected total pressure ranges. This was done in Analysis Nos. 3 and 5, and revealed highly significant differences between the average inert gas tension in "hit" and in "no hit" flights in each of three total pressure ranges examined. In retrospect this approach turns out to be seriously flawed by the fact that in "no hit" flights, inert gas tensions in compartment 15 will continue to drop until the entire programmed time at altitude has elapsed. Since the computation of dissolved inert gas tensions in flights in which decompression sickness occurred is carried out only until the first reported symptoms, it is clear that the average inert gas tension at a particular total pressure would obviously be higher in flights in which decompression sickness occurred. This was corrected in Analysis No. 6. Here, all helium flights were eliminated to avoid undue bias of the sample, since helium flights tend to produce a more rapid onset of decompression sickness than nitrogen flights. Further, we elected to correlate only the highest (that is the initial) nitrogen partial pressure in compartment 15 with success and failure of decompression. The results of this analysis show that the average initial nitrogen tension in each of three pressure ranges examined is higher for flights in which decompression sickness occurred than in "no hit" flights. This difference is statistically significant for the total pressure ranges of 150 - 200 mm Hg ($p < 0.001$) and 350 - 400 mm Hg ($p < 0.05$). In Analysis No. 7 the same correlation was attempted after reincorporating all helium flights into the statistical population. No statistically significant differences in the average initial (highest) total dissolved inert gas tensions in compartment 15 were noted.

In Analysis No. 8 we attempted to produce objective support for the subjective observation that decompression sickness develops more rapidly in helium flights than in nitrogen flights. We arrayed all flights in terms of the computed average rate of decrease in inert gas tension in compartment 15 between arrival at a particular pressure and the onset of decompression sickness. As expected, the majority (30) of all 42 helium flights in which decompression sickness was reported showed a more rapid gas loss from compartment 15 than all nitrogen flights in which decompression sickness occurred. It should be noted that in all flights compartment 15 always contained nitrogen in addition to helium, and that in most instances the computed nitrogen tension at the onset of decompression sickness was greater than that of helium.

The results of Analyses Nos. 7 and 8 point up the difficulty in evaluating so-called helium flights in which the exposure to helium is not sufficiently long to produce only helium tensions in the ascent-limiting tissues. As far as compartment 15 is concerned, such flights represent flights on variable mixtures of nitrogen and helium which cannot be treated on the same basis as pure nitrogen flights. Our approach to this dilemma was to exclude all helium flights from further consideration and to concentrate on the development of ascent-limiting gas tensions for nitrogen flights. This was done in Analysis 10 which will be discussed in greater detail later on in this report.

In Analysis No. 11 an attempt was made to determine individual susceptibility of individual subjects to decompression sickness. It was quickly realized that the wide variety of flight profiles flown by the individual subjects made such a determination impossible without giving consideration to a reasonably uniform test basis. Two graphic displays were prepared by computer in an attempt to correlate with age and weight decompression success or failure of each of 52 subjects* for the flight in which the highest Haldane Ratio was sustained. The data scatter for both correlations appeared to be entirely random in nature. This information has been transmitted to the Manned Spacecraft Center. This particular data presentation was chosen since the degree of supersaturation (Haldane Ratio) sustained in each flight may be assumed to be a more important determining factor in the production of decompression sickness than either age or weight. By selecting as the test basis for each subject only the most stressful decompression situation (highest Haldane Ratio) sustained, it could be

* For two of the 54 subjects included in the present analysis (PH 03 and PH 23) weight and age data were not available.

reasonably expected that effects of age or weight, if present, would be more clearly discernible. This did not turn out to be the case.

Analysis No. 11 also afforded an opportunity to relate the level of exercise (activity) with the susceptibility to decompression sickness of the individual subjects in this series. Visual inspection of the results yielded no apparent correlation. Detailed statistical treatment of the data did not seem warranted in view of the relatively small number of subjects, but more importantly because of the heterogeneous nature of the information (various types of flight, variations in age, height and weight, and presence or absence of helium). The effect of a single parameter such as the level of activity on decompression success can easily be studied experimentally under conditions where all other important factors which affect decompression success can be controlled. Given the nature of the data available for the present analysis it does not seem possible to arrive at a statistically valid ex post facto conclusion concerning the effect of activity on decompression success.

Analysis No. 10 represents the tabulation of all nitrogen flights, and the occurrence among those flights of instances of decompression sickness of grade 2-5 as a function of the computed maximum nitrogen tension in compartment 15 at total pressures of 150 - 200, 250 - 300, and 350 - 400 mm Hg. Within each of these three pressure ranges it is possible to find ranges of $\pi^{15}N_2$ to which can be assigned a particular decompression risk. For example (see Appendix II, Results of Analysis No. 10), there were a total of 24 flights to a total pressure of between 150 and 200 mm Hg in which the maximum value of $\pi^{15}N_2$ was computed to fall between 190 and 210 mm Hg. Five of these flights resulted in decompression sickness. Consequently, we can say that on the average 21 out of 100 subjects for whom a value of $\pi^{15}N_2$ between 190 and 210 mm Hg can be computed on arrival at 150 - 200 mm Hg total pressure, will develop decompression sickness within two hours. By the same reasoning, the percentage of risk of decompression sickness can be determined for ranges of total pressure and $\pi^{15}N_2$ for which sufficient data is available for analysis. This was done as shown in Table VI. It can be seen that only for the target pressure range of 150-200 mm. Hg is there sufficient data on hand to construct a risk profile that ranges from no decompression sickness risk to virtual certainty of decompression sickness as a function of the computed maximum nitrogen tension in compartment 15 on arrival at the target pressure. Significant data for ascent to target pressures of 200-250, 300-350, and to more than 400 mm. Hg is entirely lacking, and for the target pressure ranges of 250-300 and 350-400 mm. Hg no high decompression risk data could be obtained from the 388 flight records that were analyzed. In order to provide this information it is recommended that a substantial number of additional records of nitrogen flights to target pressures of more than 200 mm. Hg be analyzed. These target pressures should be distributed fairly equally over 50 mm. Hg pressure segments. Emphasis should be placed on flight profiles which have produced a reasonably high risk of decompression sickness.

Given a particular target pressure and a computed maximum value of $\pi_{N_2}^{15}$ at that pressure, the risk of decompression sickness, all other factors being equal, would depend upon the duration of the subject's residence at the target pressure. The sample data on hand is not large enough to analyze this temporal aspect of decompression sickness. It is possible, however, to make certain gross classifications. For example, by considering only those flights as "hit" flights in which decompression sickness occurred within a specified time at the target pressure, a new risk level of decompression sickness can be computed for the evaluation of flights in which exposure to the target altitude is limited to that specified time. The risks of decompression sickness presented in Table VI presume an essentially infinite stay at the target pressure. For the pressure range of 150-200 mm. Hg these risks were recomputed by considering as "no hit" flights all those flights in which decompression sickness occurred more than 2 hr. after arrival at the target pressure.

These new 2-hr. risk levels, as shown in Table VI, are not materially different from the original, infinite-time risk levels. As the exposure to the target pressure decreases to well below 2 hr., these risk levels can be expected to decrease considerably. A graphic display of infinite-time risk levels as a function of maximum $\pi_{N_2}^{15}$ are shown in Fig. 4 for three ranges of target pressure.

Diving experience, especially by the United States Navy has shown that certain levels of calculated tissue inert gas tensions are compatible with safe ascent to surface pressure. From this experience Workman (1965) has extracted a set of ascent-limiting helium and nitrogen tensions for several body compartments. By the linear extra- and interpolation of these data it is possible to arrive at an extension of these ascent-limiting values to altitude. Values so obtained for nitrogen dissolved in compartment 15 are presented in Table IX. These values are quite high as compared to those extracted by our current analysis of 388 altitude flights (Table VI). It is therefore obvious that a linear extrapolation of ascent-limiting tissue tensions of inert gases derived from diving experience does not lead to fruitful results in assessing the risk of altitude decompression sickness.

Six altitude decompression profiles were submitted by the Manned Spacecraft Center for an evaluation of their potential risk of decompression sickness. These profiles are summarized in Table VII. Maximum values of $\pi_{N_2}^{15}$ were computed at each discontinuity of these profiles, and the 2-hr. risk of decompression associated with these values at the total pressure range at which they occurred was determined from Table VI. The results of this evaluation are presented in Table VIII

It is necessary to recall that the criteria of decompression sickness on which Analysis No. 10 is based are broad and encompass a variety of subjectively felt abnormalities (see page 12 for a definition of grades 2-5 of decompression sickness) This tends to produce a much higher apparent risk of decompression sickness than would be encountered in situations where the subject may be reluctant to report even severe pain, such as in decompression runs designed to determine continued fitness to fly a military airplane. D.I. Fryer (personal communication) for example reports a 4% incidence of decompression sickness in pilots so tested by exposing them to 28,000 ft. (246.8 mm. Hg) for 2 hr. This profile entails a maximum value of $\pi^{15}_{N_2}$ equal to 580 mm. Hg which, according to Table VI should result in an incidence of decompression sickness of all grades of more than 31%. Inspection of the primary computer printout records of all nitrogen flights to a target pressure of 250-300 mm. Hg shows that the most severe grade of decompression sickness reported was 3, defined as slight discomfort or slight pain. It seems obvious that a subject whose flying career is at stake would not readily report such a tolerable symptom of decompression sickness, while a subject participating in a scientific experiment would be positively motivated to do so. In the absence of objective means of assessing the presence of decompression sickness without the cooperation of the subject discrepancies such as this must be expected in evaluating the incidence of altitude decompression sickness. On the other hand, computer analyses of additional altitude flight records would create a body of data sufficiently large to develop decompression risk levels differentiated by the severity of the symptoms that are to be expected.

In addition to these eleven computer analyses, we prepared graphic displays of the time course of inert gas tensions computed for compartments No. 8, 9, 10, 11, 13, 14 and 15 of 20 altitude profiles, each flown by two or more subjects. This information was submitted to the Manned Spacecraft Center together with a numerical computer printout of all calculated and recorded information associated with the flights represented by these 20 profiles. A list of the chart, flight and subject numbers involved is presented as Appendix III to this report. The detailed results of all analyses conducted under Contract NAS9-6978 are being retained by the contractor. Information available on the contractor's primary computer printouts or magnetic tape records which is not presented in this report can be made available to the Manned Spacecraft Center on request. Such requests should be directed to: Dr. H. R. Schreiner, Research Supervisor, Union Carbide Corporation, Linde Division Research Laboratory, P. O Box 44, Tonawanda, N Y. 14150; telephone (716) 877-1600, Ext. 8073.

TABLE VI

Risks of Decompression Sickness of Grade 2-5 as a Function of Computed Maximum Nitrogen Tension in the Slowest Gas Transport Compartment of the Human Body ($\pi^{15}_{N_2}$)

(Interpretation of the Results of Analysis No. 10)

| Target Pressure Range (mm. Hg) | Range of Maximum $\pi^{15}_{N_2}$ (mm. Hg) | Percent Risk of Decompression Sickness | Percent Risk of Decompression Sickness* |
|---|---|---|---|
| 350-400 | 0-565 | 0 | |
| | 565-582 | 11 | |
| 250-300 | 0-415 | 0 | |
| | 415-425 | 13 | |
| | 455-467 | 31 | |
| 150-200 | 0-190 | 0 | 0 |
| | 190-210 | 21 | 21 |
| | 225-240 | 25 | 25 |
| | 240-295 | 33 | 29 |
| | 305-425 | 36 | 36 |
| | 425-465 | 41 | 35 |
| | 465-480 | 85 | 83 |

* With the onset of symptoms occurring within 2 hr. after arrival at pressure range shown.

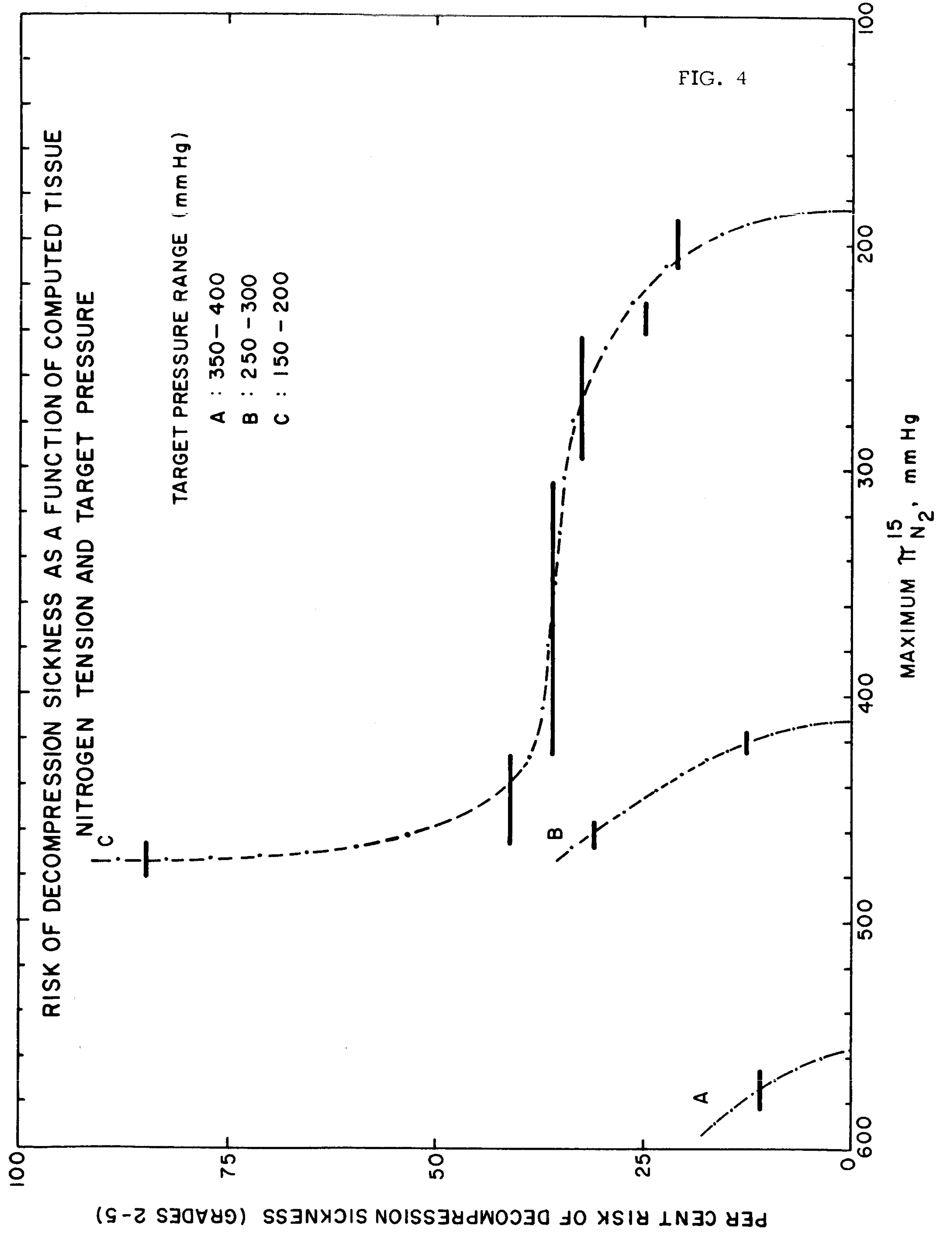

RISK OF DECOMPRESSION SICKNESS AS A FUNCTION OF COMPUTED TISSUE NITROGEN TENSION AND TARGET PRESSURE
TARGET PRESSURE RANGE (mm Hg)
A : 350 – 400
B : 250 – 300
C : 150 – 200
A
B
C
100
75
50
25
0
600
500
400
300
200
100
MAXIMUM $\pi^{15}_{N_2}$, mm Hg
PER CENT RISK OF DECOMPRESSION SICKNESS (GRADES 2-5)

FIG. 4

TABLE VII

Altitude Decompression Profiles Submitted by the

Manned Spacecraft Center for Evaluation of Their

Potential Risk of Decompression Sickness

| | |
|---|---|
| Case 1 | Two hours pre-oxygenation at 760 mm. Hg followed by ascent in one minute to 181 mm. Hg, and residence at this pressure for two hours while on 100% oxygen. |
| Case 2 | Three hours pre-oxygenation at 760 mm. Hg. followed by ascent in one minute to 181 mm. Hg, and residence at this pressure for two hours while on 100% oxygen. |
| Case 3 | Four hours pre-oxygenation at 760 mm. Hg followed by ascent in one minute to 181 mm. Hg, and residence at this pressure for two hours while on 100% oxygen. |
| Case 4 | Three hours pre-oxygenation at 760 mm. Hg, shift to 60% oxygen, 40% nitrogen followed by ascent in one minute to 258 mm. Hg, and residence at this pressure for 4 hr. Shift to 100% oxygen, ascent to 181 mm. Hg in one minute, and residence at this pressure for 2 hr. |
| Case 5 | Four hours pre-oxygenation at 760 mm. Hg, shift to 45% oxygen, 55% nitrogen followed by ascent in 1 min. to 481 mm. Hg, and residence at this pressure for 3 hr. Shift to 100% oxygen, ascent to 181 mm. Hg. in 1 min., and residence at this pressure for 2 hr. |
| Case 6 | Residence at 1452 mm. Hg for 24 hr. breathing 20% oxygen, 80% nitrogen, followed by ascent to 760 mm. Hg in 1 min., and residence at this pressure for 2 hr. Without shift in gas mixture, ascent to 564 mm. Hg in 1 min. followed by residence at this pressure for 2 hr. |

TABLE VIII

Predicted Risk of Decompression Sickness of Grade 2-5

Associated With Six Altitude Decompression

Profiles Submitted for Evaluation*

| Case No. | Target Pressure (mm Hg) | Maximum $\pi^{15}_{N_2}$ at Target Altitude (mm Hg) | Percent Risk of Decompression Sickness** |
|---|---|---|---|
| 1 | 181 | 470 | 83 |
| 2 | 181 | 426 | 35 |
| 3 | 181 | 387 | 36 |
| 4 | 258 | 427 | 13 |
| | 181 | 315 | 36 |
| 5 | 481 | 388 | 0 |
| | 181 | 350 | 36 |
| 6 | 564 | 1029 | *** |

* See Table VII

** With the onset of symptoms within 2 hours after arrival at target pressure shown.

*** Workman's ascent-limiting nitrogen partial pressure (M value) extrapolated to 546 mm Hg is equal to 946 mm Hg (see Table IX). On this basis Case 6 should be associated with considerable risk of decompression sickness.

TABLE IX

Suggested Ascent-Limiting Tissue Nitrogen Tensions
for Compartment 15 Extrapolated From
Workman's (1965) Diving Data

| Target Pressure (mm Hg) | Suggested Maximum $\pi^{15}_{N_2}$ (mm Hg) |
|---|---|
| 760 | 1152 |
| 710 | 1100 |
| 660 | 1049 |
| 610 | 998 |
| 560 | 946 |
| 510 | 895 |
| 460 | 844 |
| 410 | 792 |
| 360 | 741 |
| 310 | 690 |
| 260 | 638 |
| 210 | 587 |
| 160 | 536 |

# APPENDIX I

## Glossary of Terms

| Term | Definition |
|---|---|
| "Clean" | Symptoms of decompression sickness not reported by the subject |
| "Clean" flight | The initial portion of a flight prior to the first report of symptoms of decompression sickness by the subject |
| Discontinuity | Every abrupt change in total pressure or composition of inspired gas during a flight |
| Flight | The tissue course of total pressure and inspired gas composition to which a given individual subject is exposed experimentally |
| Flight character | A given flight is characterized as either a "no hit" or a "hit" flight, depending on whether or not symptoms of decompression sickness were reported by the subject. A "no hit" flight is considered "clean" throughout; a "hit" flight is considered "clean" until the first report of symptoms of decompression sickness by the subject |
| Flight number | A 5-digit identification of an altitude flight by one individual subject |
| Haldane Ratio | The sum of dissolved inert gas partial pressures calculated for a particular hypothetical tissue compartment divided by the total pressure |
| "Hit" | Symptoms of decompression sickness reported by the subject |
| "Hit" flight | A flight in which symptoms of decompression sickness were reported by the subject |
| "Hit" score | The severity of reported symptoms of decompression sickness (or their absence) expressed as "grades" ranging from -1 to +5. For grading criteria see text. |

| | |
|---|---|
| "No Hit" flight | A flight in which no symptoms of decompression sickness were reported by the subject. |
| Sigma Pi 15 ($\Sigma\pi_{15}$) | The sum of dissolved inert gas partial pressures calculated for the 15th hypothetical tissue compartment of the Tonawanda II Gas Transport Model (see text) |
| Subject identification | A 3-digit unique identification of each subject preceded by 2 digits identifying the geographic location where data was generated |
| Supersaturation | A condition in which the calculated total pressure of all inert gases dissolved in one or more body compartments exceeds the barometric pressure to which the subject is exposed. |
| Target Altitude | The altitude attained by a given flight. Depending on the flight profile, there may be more than one target altitude for a given flight. |
| Target Pressure | The total pressure prevailing at the target altitude. |

# APPENDIX II

## Objectives and Results of Eleven Computer Analyses of 388 Altitude Flight Records

## Analysis No. 1

Objective: Correlate ranges of Haldane Ratios sustained in the 15th tissue compartment during each flight with reported decompression sickness ("hit").

Execution: Select several ranges of Haldane Ratios (in units of 0.5) and list for each range those flights in which a ratio falling within that range occurred in the 15th compartment. Show the number of such occurrences in each range. For each range, list the identification numbers of those flights in which decompression sickness had not developed at the time a given ratio was sustained ("clean" flights) and, separately, those of "hit" flights. Flights which were "clean" when a particular ratio was sustained, but which subsequently became "hit" flights are to be marked by an asterisk. The ratios are to be tabulated (by identifying flight number, each flight number constituting one entry) up to and including the first report of a "hit" (see definition below). Accordingly, there will be only one "hit" reported in each "hit" flight.

Definition: "Hit" flights are considered "clean" until the first report of a "hit" score of 2 or higher, except that if the highest "hit" score attained throughout the flight is 2, the flight is considered to be a "no hit" flight.

For each ratio range list total number of flights, number of "hit" flights and percentage of "hit" flights.

Results of Anal ysis No. 1

| Haldane Ratio Range | Total Number of Flights | Number of Flights Resulting in "Hits" of Grade 3-5* | |
|---|---|---|---|
| | | Number | Per Cent |
| 0 - 0.50 | 212 | 1 | 0.472 |
| 0.51 - 1.00 | 340 | 7 | 2.059 |
| 1.01 - 1.50 | 281 | 58 | 20.641 |
| 1.51 - 2.00 | 383 | 51 | 13.316 |
| 2.01 - 2.50 | 121 | 48 | 39.669 |
| 2.51 - 3.00 | 55 | 8 | 14.545 |
| | | 173 | |

* see definition.

# Analysis No. 2

Objective: Correlate ranges of Haldane Ratios sustained in the 15th tissue compartment during each flight with reported decompression sickness ("hit).

Execution: Select several ranges of Haldane Ratios (in units of 0.5) and list for each range those flights in which a ratio falling within that range occurred in the 15th compartment. Show the number of such occurrences in each range. For each range, list the identification numbers of those flights in which decompression sickness had not developed at the time a given ratio was sustained ("clean" flights) and, separately, those of "hit" flights. Flights which were "clean" when a particular ratio was sustained, but which subsequently became "hit" flights are to be marked by an asterisk. The ratios are to be tabulated (by identifying flight number, each flight number constituting one entry) up to and including the first report of a "hit" (see definition below). Accordingly, there will be only one "hit" reported in each "hit" flight.

Definition: "Hit" flights are considered "clean" until the first report of a "hit" score of 3 or higher, except that if the highest "hit" score attained throughout the flight is 3, the flight is considered to be a "no hit" flight.

For each ratio range list total number of flights, number of "hit" flights and percentage of "hit" flights.

Results of Analysis No. 2

| Haldane Ratio Range | Total Number of Flights | Number of Flights Resulting in "Hits" of Grade 4-5* | |
|---|---|---|---|
| | | Number | Per Cent |
| 0 - 0.50 | 271 | 0 | 0 |
| 0.51 - 1.00 | 348 | 7 | 2.011 |
| 1.01 - 1.50 | 293 | 36 | 12.287 |
| 1.51 - 2.00 | 378 | 31 | 8.201 |
| 2.01 - 2.50 | 117 | 29 | 24.786 |
| 2.51 - 3.00 | 54 | 5 | 9.259 |
| | | 108 | |

* see definition.

## Analysis No. 3

Objective: For each of several ranges of total pressure, determine correlation between character of flight ("clean," "no hit," or "hit") and sum of inert gas pressures calculated for 15th tissue compartment at each discontinuity.

Execution: For each 50-mm. Hg range of total pressure, compute the average, minimum and maximum value of $\Sigma \pi_{15}$ at each discontinuity for all "no hit" flights, all "clean" flights, and at the moment of the first "hit" report. In this categorization, each discontinuity in each flight is associated with a calculated value of $\Sigma \pi_{15}$. The value of $\Sigma \pi_{15}$ calculated at the moment of the first "hit" report is the final $\Sigma \pi_{15}$ data point generated by a "hit" flight. Accordingly, there is only one "hit" value of $\Sigma \pi_{15}$ stated for each "hit" flight.

In each pressure range also show the number of data points giving rise to the average values of $\Sigma \pi_{15}$ listed. Use "hit" definition of Analysis No. 1.

## Results of Analysis No. 3

| Pressure | "No Hit" Flights | | | | "Clean" Flights | | | | "Hit" Flights | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\Sigma \pi_{15}$ | | | | $\Sigma \pi_{15}$ | | | | $\Sigma \pi_{15}$ | | | |
| Range | Min. | Max. | Avg. | No. | Min. | Max. | Avg. | No. | Min. | Max. | Avg. | No. |
| 800-750 | 43.45 | 474.61 | 296.84 | 235 | 416.46 | 476.51 | 454.89 | 67 | 0 | 0 | 0 | 0 |
| 750-700 | 139.47 | 462.40 | 319.67 | 96 | 417.33 | 462.40 | 458.23 | 31 | 0 | 0 | 0 | 0 |
| 600-550 | 0 | 0 | 0 | 0 | 489.69 | 496.64 | 494.99 | 6 | 0 | 0 | 0 | 0 |
| 500-450 | 168.35 | 168.35 | 168.35 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 450-400 | 208.12 | 254.40 | 231.26 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400-350 | 58.00 | 581.06 | 422.63 | 228 | 57.84 | 578.75 | 473.71 | 136 | 264.58 | 563.93 | 427.04 | 20 |
| 350-300 | 173.07 | 177.02 | 175.05 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 300-250 | 140.49 | 465.75 | 335.05 | 162 | 191.04 | 466.83 | 398.15 | 83 | 220.04 | 470.55 | 342.73 | 27 |
| 250-200 | 0 | 0 | 0 | 0 | 285.13 | 383.91 | 350.33 | 6 | 333.21 | 385.04 | 359.13 | 2 |
| 200-150 | 43.51 | 470.64 | 264.99 | 479 | 57.75 | 475.73 | 369.83 | 108 | 56.84 | 467.53 | 337.37 | 124 |

Pressure ranges not shown were not encountered in this analysis.

## Analysis No. 4

Objective: Correlate highest Haldane Ratio sustained in 15th tissue compartment with report of decompression sickness ("hit").

Execution: Array all flights in terms of increasing maximum Haldane Ratio sustained in 15th compartment. Indicate for each flight the maximum "hit" score attained. Sub-array all flights into discrete ranges of maximum Haldane Ratio sustained and determine for each such range the total number of flights, and number of flights in which "hits" were reported, according to their score. Develop this information and percentage of incidence for "hit" scores 2-5, 3-5, 4-5, and 5.

Results of Analysis No. 4

| Haldane Ratio Range* | Total Number of Flights | Number of Flights Resulting in "Hits" of Grade: 2-5 | (%) | 3-5 | (%) | 4-5 | (%) | 5 | (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1.41-1.60 | 86 | 28 | (33) | 22 | (26) | 11 | (13) | 4 | (5) |
| 1.61-1.80 | 126 | 67 | (53) | 58 | (46) | 40 | (32) | 12 | (10) |
| 1.81-2.00 | 54 | 28 | (52) | 26 | (48) | 16 | (30) | 6 | (11) |
| 2.01-2.20 | 17 | 11 | (65) | 10 | (59) | 4 | (24) | 0 | (0) |
| 2.21-2.40 | 53 | 23 | (43) | 21 | (40) | 14 | (26) | 5 | (9) |
| 2.41-2.60 | 27 | 20 | (74) | 18 | (67) | 10 | (37) | 4 | (15) |
| 2.61-2.80 | 24 | 21 | (87) | 17 | (71) | 12 | (50) | 4 | (17) |
| 2.81-3.00 | 1 | 1 | | 1 | | 1 | | 0 | |
| | 388 | 199 | (51) | 173 | (44) | 108 | (28) | 35 | (9) |

* Maximum Haldane Ratio sustained during flight in 15th compartment.

# Analysis No. 5

Objective: For each range of total pressure for which sufficient data is on hand, determine the difference, and the statistical significance of this difference in average values of $\Sigma \pi_{15}$ between "no hit" flights and all flights in which a "hit" was reported.

Execution: For the ranges of 150-200, 250-300, and 350-400 mm. Hg, determine for each discontinuity the value of $\Sigma \pi_{15}$ for all "no hit" flights and for all flights in which a "hit" was reported (according to the definition of Analysis No. 1). Compute the minimum, maximum, and average value of $\Sigma \pi_{15}$ for both types of flights and the t values (Student's t for unpaired variates) associated with the differences between the average $\Sigma \pi_{15}$ values in each pressure range.

## Results of Analysis No. 5

| Pressure | "No Hit" Flights | | | | "Hit" Flights | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\Sigma T_{15}$ | | | | $\Sigma T_{15}$ | | | | |
| Range | Min. | Max. | Avg. | No. | Min. | Max. | Avg. | No. | T-Value |
| 400-350 | 58.00 | 581.06 | 422.63 | 228 | 57.84 | 578.75 | 467.72 | 156 | - 3.18269 |
| 300-250 | 140.49 | 465.75 | 335.05 | 162 | 191.04 | 470.55 | 384.55 | 110 | - 3.87403 |
| 200-150 | 43.51 | 470.64 | 264.99 | 479 | 56.84 | 475.73 | 352.47 | 232 | -12.64600 |

## Analysis No. 6

Objective: For each range of total pressure for which sufficient data is on hand, determine the difference and the statistical significance of this difference in the highest value of $\pi^{15}_{N_2}$ between "no hit" flights and all flights in which a "hit" was reported.

Execution: For the ranges of 150 - 200, 250 - 300, and 350 - 400 mm Hg, determine the highest value of the calculated dissolved nitrogen pressure in the 15th tissue compartment ($\pi^{15}_{N_2}$) experienced at any discontinuity for each nitrogen flight. Thus there will be only one stated value of $\pi^{15}_{N_2}$ per flight and pressure range. Eliminate from consideration all flights in which helium was breathed. Compute the minimum, maximum, and average of the highest values of $\pi^{15}_{N_2}$ in all flights for which a "hit" was reported (according to the definition of Analysis No. 1) and in all "no hit" flights. Also compute the t values (Student's t for unpaired variates) associated with the differences between the average highest $\pi^{15}_{N_2}$ values in each pressure range. Disregard all calculated values of $\pi^{15}_{N_2}$ obtained after the first report of a "hit" as defined by Analysis No. 1.

## Results of Analysis No. 6

| Pressure | "No Hit" Flights $\pi\,^{15}N_2$ | | | | "Hit" Flights $\pi\,^{15}N_2$ | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Range | Min. | Max. | Avg. | No. | Min. | Max. | Avg. | No. | T-Value |
| 400-350 | 427.95 | 581.06 | 554.77 | 80 | 565.36 | 576.66 | 572.08 | 33 | -2.27437 |
| 300-250 | 155.31 | 465.75 | 446.41 | 65 | 291.28 | 466.83 | 456.81 | 51 | -1.43027 |
| 200-150 | 57.92 | 470.64 | 294.54 | 179 | 57.75 | 475.73 | 359.45 | 96 | -5.50173 |

## Analysis No. 7

Objective: For each range of total pressure for which sufficient data is on hand, determine the difference in the highest value of $\Sigma\pi_{15}$ and the significance of this difference between "no hit" flights and all flights in which a "hit" was reported.

Execution: For the ranges of 150 - 200, 250 - 300, and 350 - 400 mm Hg, determine the highest value of $\Sigma\pi_{15}$ experienced at any discontinuity within a given pressure range for each helium flight. Thus there will be only one stated value of $\Sigma\pi_{15}$ per flight and pressure range. Eliminate from consideration all flights in which helium was not breathed. Compute the minimum, maximum, and average of the highest values of $\Sigma\pi_{15}$ in all flights for which a "hit" was recorded (according to the definition of Analysis No. 1) and in all "no hit" flights. Also compute the t values (Student's t for unpaired variates) associated with the differences between the average highest $\Sigma\pi_{15}$ values in each pressure range. Disregard all calculated values $\Sigma\pi_{15}$ obtained after a "hit" as defined by Analysis No. 1.

## Results of Analysis No. 7

| Pressure Range | "No Hit" Flights $\Sigma\pi_{15}$ Min. | Max. | Avg. | No. | "Hit" Flights $\Sigma\pi_{15}$ Min. | Max. | Avg. | No. | T-Value |
|---|---|---|---|---|---|---|---|---|---|
| 400-350 | 563.93 | 578.75 | 569.90 | 31 | 563.93 | 578.75 | 570.88 | 42 | -0.85027 |
| 300-250 | 0.0 | 0.0 | 0.0 | 0 | 392.89 | 395.35 | 394.14 | 3 | 0.0 |
| 200-150 | 332.11 | 459.51 | 370.56 | 28 | 324.05 | 459.51 | 394.97 | 29 | -1.86885 |

## Analysis No. 8

Objective: Correlate the rapidity of onset of pain-type decompression sickness with the rate of inert gas loss from the 15th tissue compartment.

Execution: Select all flights resulting in hits of grades 3 - 5. Determine the running time at the instance a hit of grade 3, 4, or 5 is first reported. Then determine the value of $\Sigma\pi_{15}$ at the last discontinuity immediately preceding the instant of the "hit". Divide the difference between $\Sigma\pi_{15}$ at the last discontinuity and at the onset of the "hit" by the time elapsed $\Delta t$ between these two events. If this ratio is negative (indicating gas uptake) show its negativity. Print out all flight numbers arranged in order of decreasing associated values of $\Delta\Sigma\pi_{15}/\Delta t$; also print out values of $\pi^{15}_{N_2}$ and $\pi^{15}_{He}$ at the last discontinuity and at the first "hit" of grade 3 or higher.

## Results of Analysis No. 8

(Summary)

| Number of Flights | Helium Breathed | $\Delta\Sigma\pi_{15}/\Delta t$ Range |
|---|---|---|
| 30 | yes | 1.224 - 0.889 |
| 110 | no | 0.777 - 0.377 |
| 1 | yes | 0.376 |
| 13 | no | 0.374 - 0.339 |
| 3 | yes | 0.334 - 0.333 |
| 1 | no | 0.332 |
| 5 | yes | 0.332 - 0.323 |
| 2 | no | 0.322 - 0.312 |
| 1 | yes | 0.308 |
| 3 | no | 0.302 - 0.287 |
| 1 | yes | 0.170 |
| 1 | no | 0.091 |
| 1 | yes | -0.367 |
| 172 | | |

## Analysis No. 9

Objective: To ascertain the reasons for the abnormally low rate of incidence of decompression sickness for flights with a maximum Haldane Ratio in the range of 2.21 - 2.40 as shown by Analysis No. 4.

Execution: For all flights in which a maximum Haldane Ratio between 2.21 and 2.40 was attained, print out the following information: Flight Number, Maximum Haldane Ratio (in increasing order), total pressure, subject identification number, and maximum grade of "hit" reported for the flight.

Results of Analysis No. 9

| Flight No. | Haldane Ratio | Total Pressure | Subject Ident. No. | Maximum Grade of Hit |
|---|---|---|---|---|
| 25219 | 2.275 | 179.34 | PH 28 | 0 |
| 25071 | 2.351 | 176.86 | PH 09 | 5 |
| 25124 | 2.355 | 176.86 | PH 13 | 0 |
| 25258 | 2.355 | 176.86 | PH 33 | 3 |
| 25238 | 2.355 | 176.86 | PH 30 | 0 |
| 25009 | 2.369 | 180.44 | PH 02 | 0 |
| 25044 | 2.369 | 180.38 | PH 06 | 0 |
| 25126 | 2.369 | 180.89 | PH 14 | 5 |
| 25220 | 2.369 | 180.89 | PH 29 | 0 |
| 25260 | 2.369 | 180.89 | PH 34 | 3 |
| 25210 | 2.373 | 181.25 | PH 27 | 4 |
| 25247 | 2.375 | 179.39 | PH 32 | 0 |
| 25030 | 2.375 | 179.39 | PH 05 | 0 |
| 25020 | 2.375 | 179.39 | PH 03 | 0 |
| 25007 | 2.376 | 179.39 | PH 01 | 0 |
| 25139 | 2.376 | 179.34 | PH 15 | 0 |
| 25204 | 2.376 | 179.34 | PH 26 | 0 |
| 25196 | 2.376 | 179.34 | PH 25 | 0 |
| 25088 | 2.379 | 178.88 | PH 11 | 3 |
| 25075 | 2.379 | 178.88 | PH 10 | 3 |
| 25171 | 2.379 | 178.88 | PH 20 | 5 |
| 25032 | 2.379 | 178.88 | PH 05 | 2 |
| 25049 | 2.379 | 178.62 | PH 07 | 4 |
| 25189 | 2.379 | 178.62 | PH 24 | 3 |
| 25106 | 2.379 | 178.62 | PH 12 | 4 |
| 25162 | 2.379 | 178.62 | PH 19 | 4 |
| 25163 | 2.379 | 178.68 | PH 19 | 0 |
| 25022 | 2.379 | 178.68 | PH 04 | 4 |
| 25057 | 2.379 | 178.86 | PH 07 | 0 |
| 25081 | 2.379 | 178.86 | PH 10 | 0 |
| 25094 | 2.379 | 178.86 | PH 11 | 0 |
| 25178 | 2.379 | 178.86 | PH 20 | 5 |
| 25108 | 2.380 | 179.97 | PH 12 | 0 |
| 25279 | 2.380 | 179.97 | PH 36 | 4 |
| 25270 | 2.380 | 179.97 | PH 35 | 0 |

| | | | | |
|---|---|---|---|---|
| 25155 | 2.381 | 180.60 | PH 18 | 2 |
| 25280 | 2.381 | 180.60 | PH 36 | 5 |
| 25272 | 2.381 | 180.60 | PH 35 | 0 |
| 25029 | 2.381 | 180.44 | PH 04 | 0 |
| 25195 | 2.381 | 180.44 | PH 24 | 0 |
| 25160 | 2.381 | 180.44 | PH 18 | 0 |
| 25170 | 2.381 | 180.44 | PH 19 | 0 |
| 25115 | 2.381 | 180.38 | PH 12 | 0 |
| 25096 | 2.381 | 180.38 | PH 11 | 0 |
| 25221 | 2.382 | 182.33 | PH 29 | 0 |
| 25083 | 2.382 | 182.33 | PH 10 | 0 |
| 25148 | 2.382 | 182.33 | PH 17 | 3 |
| 25058 | 2.382 | 182.33 | PH 08 | 4 |
| 25290 | 2.382 | 182.33 | PH 37 | 3 |
| 25097 | 2.382 | 182.33 | PH 11 | 0 |
| 25038 | 2.382 | 182.51 | PH 05 | 4 |
| 25050 | 2.386 | 178.17 | PH 07 | 0 |
| 25161 | 2.387 | 180.38 | PH 18 | 4 |

## Analysis No. 10

Objective: To assess the distribution of maximum values of $\pi^{15}_{N_2}$ sustained in each range of total pressure for which sufficient data is on hand.

Execution: Determine the highest value of calculated dissolved nitrogen pressure in the 15th tissue compartment ($\pi^{15}_{N_2}$) experienced at any discontinuity or at the moment of the first reported "hit" for each nitrogen flight. Eliminate from consideration all flights in which helium was breathed. In each of the following three pressure ranges (150 - 200, 250 - 300, and 350 - 400 mm Hg) tabulate the values of $\pi^{15}_{N_2}$ in increasing order of magnitude, and indicate for each entry the character of the flight ("hit" or "no hit"). If the first "hit" was sustained within the pressure range for which the tabulation is made, show the "hit" score as well. If the first "hit" of a "hit" flight did not occur in the pressure range for which the tabulation is made, show the total pressure at which the first hit was reported.

## Results of Analysis No. 10

A. Pressure Range 400 - 350 mm Hg

| $\pi^{15}N_2$ | No. of Flights with "Hits" of Grade 2 - 5 | Total Number of Flights | Cumulative Total No. of Flights |
|---|---|---|---|
| 0 - 565 | 0 | 12 | 12 |
| 565.1 - 570 | 3 | 18 | 30 |
| 570.1 - 575 | 3 | 31 | 61 |
| 575.1 - 582 | 2 | 27 | 88 |
| | 8 | 88 | |

B. Pressure Range 300 - 250 mm Hg

| $\pi^{15}N_2$ | No. of Flights with "Hits" of Grade 2 - 5 | Total Number of Flights | Cumulative Total No. of Flights |
|---|---|---|---|
| 0 - 415 | 0 | 3 | 3 |
| 415.1 - 420 | 1 | 6 | 9 |
| 420.1 - 425 | 0 | 2 | 11 |
| 455.1 - 460 | 17 | 42 | 53 |
| 460.1 - 465 | 6 | 34 | 87 |
| 465.1 - 467 | 2 | 4 | 91 |
| | 26 | 91 | |

C. Pressure Range 200 - 150 mm Hg

| $\pi^{15}N_2$ | No. of Flights with "Hits" of Grade 2-5 | Total Number of Flights | Cumulative Total No. of Flights |
|---|---|---|---|
| 58 | 1 | 2 | 2 |
| 185.1 - 190 | 0 | 14 | 16 |
| 190.1 - 195 | 3 | 14 | 30 |
| 205.1 - 210 | 2 | 10 | 40 |
| 225.1 - 230 | 10 | 24 | 64 |
| 230.1 - 235 | 0 | 3 | 67 |
| 235.1 - 240 | 2 | 22 | 89 |
| 240.1 - 245 | 0 | 3 | 92 |
| 250.1 - 255 | 0 | 3 | 95 |
| 260.1 - 265 | 2 | 21 | 116 |

## Analysis No. 11

Objective: To correlate individual susceptibility to decompression sickness with maximum Haldane Ratio sustained.

Execution: Arrange all nitrogen flights in order of decreasing maximum Haldane Ratio sustained. Print out the following information for each flight (omit all flights during which helium was breathed).

Running Number (1, 2, ...), Flight Number, Subject Identification Number, Maximum Haldane Ratio Sustained, Maximum Hit Grade Sustained, Yes or No statement concerning in-flight exercise, total number of nitrogen flights of the subject, number of nitrogen "hit" flights (definition of analysis 1) of subject, and ratio of "hit" flights to total flights (all nitrogen) of subject.

Results of Analysis No. 11

(Summary)

| Subject Identification No. | Incidence of Decompression Sickness (Grades 2 - 5) |
|---|---|
| PH 1 | 5/6 |
| PH 2 | 1/6 |
| PH 3 | 0/4 |
| PH 4 | 4/7 |
| PH 5 | 6/12 |
| PH 6 | 1/5 |
| PH 7 | 5/9 |
| PH 8 | 7/8 |
| PH 9 | 3/9 |
| PH 10 | 4/13 |
| PH 11 | 7/18 |
| PH 12 | 2/10 |
| PH 13 | 2/9 |
| PH 14 | 5/7 |
| PH 15 | 5/7 |
| PH 16 | 4/6 |
| PH 17 | 3/8 |
| PH 18 | 1/7 |
| PH 19 | 2/9 |
| PH 20 | 3/8 |
| PH 21 | 4/7 |
| PH 22 | 0/2 |
| PH 23 | 0/1 |
| PH 24 | 0/6 |
| PH 25 | 0/2 |
| PH 26 | 2/7 |
| PH 27 | 4/6 |
| PH 28 | 2/7 |
| PH 29 | 2/10 |
| PH 30 | 3/8 |
| PH 31 | 2/2 |
| PH 32 | 3/7 |
| PH 33 | 5/9 |
| PH 34 | 4/9 |
| PH 35 | 1/9 |

| | |
|---|---|
| PH 36 | 4/7 |
| PH 37 | 6/8 |
| SA 38 | 0/8 |
| SA 39 | 2/3 |
| SA 40 | 3/5 |
| SA 41 | 3/7 |
| SA 42 | 6/8 |
| SA 43 | 4/8 |
| SA 44 | 4/7 |
| SA 45 | 0/8 |
| SA 46 | 0/8 |
| SA 47 | 0/8 |
| SA 48 | 3/8 |
| SA 49 | 5/7 |
| SA 50 | 4/7 |
| SA 51 | 1/1 |
| SA 52 | 2/7 |
| SA 53 | 1/7 |
| SA 54 | 3/6 |

APPENDIX III

Chart, Flight, and Subject Numbers Involved in the Graphic Analyses of 20 Flight Profiles Prepared for the National Aeronautics and Space Administration, Manned Spacecraft Center Under Contract NAS9-6978

| Chart No. | Flight No. | Subject No. |
|---|---|---|
| 1 | 25-241 | PH 32 |
| | 25-141 | PH 16 |
| | 25-213 | PH 28 |
| | 25-239 | PH 31 |
| 2 | 25-054 | PH 7 |
| | 25-167 | PH 19 |
| | 25-193 | PH 24 |
| | 25-026 | PH 4 |
| 3 | 25-207 | PH 27 |
| | 25-199 | PH 26 |
| | 25-134 | PH 15 |
| | 25-002 | PH 1 |
| 4 | 25-201 | PH 26 |
| | 25-004 | PH 1 |
| | 25-209 | PH 27 |
| 5 | 25-123 | PH 13 |
| | 25-257 | PH 33 |
| | 25-237 | PH 30 |
| 6 | 25-206 | PH 27 |
| | 25-198 | PH 26 |
| | 25-001 | PH 1 |
| 7 | 25-242 | PH 32 |
| | 25-214 | PH 28 |
| | 25-142 | PH 16 |
| | 25-240 | PH 31 |
| 8 | 25-006 | PH 1 |
| | 25-138 | PH 15 |
| 9 | 25-200 | PH 26 |
| | 25-135 | PH 15 |
| | 25-208 | PH 27 |
| | 25-003 | PH 1 |

| | | |
|---|---|---|
| 10 | 25-335 | SA 44 |
| | 25-350 | SA 46 |
| 11 | 25-337 | SA 44 |
| | 25-359 | SA 47 |
| 12 | 25-322 | SA 42 |
| | 25-360 | SA 47 |
| 13 | 25-345 | SA 45 |
| | 25-321 | SA 42 |
| 14 | 25-396 | SA 53 |
| | 25-389 | SA 52 |
| 15 | 25-383 | SA 50 |
| | 25-338 | SA 44 |
| 16 | 25-369 | SA 48 |
| | 25-331 | SA 43 |
| 17 | 25-336 | SA 44 |
| | 25-401 | SA 54 |
| 18 | 25-368 | SA 48 |
| | 25-403 | SA 54 |
| 19 | 25-370 | SA 49 |
| | 25-332 | SA 44 |
| 20 | 25-305 | SA 40 |
| | 25-310 | SA 41 |

# APPENDIX IV

## REFERENCES:


Jones, H.B.
Respiratory System: Nitrogen Elimination.
in: Medical Physics 2: 855-871, ed. O. Glasser,
Chicago: Yearbook Publ., 1950.

McIver, R.G., T.A. Allen, S.E. Beard and R.W. Bancroft
Bends in Simulated Extra Vehicular Activity,
In: Lectures in Aerospace Medicine, February 1967,
USAF School of Aerospace Medicine, San Antonio, Texas

Rahn, H. and W.O. Fenn
A Graphical Analysis of the Respiratory Gas Exchange.
The $O_2$-$CO_2$ Diagram. Washington, D.C.:
The Am. Physiol. Soc., 1955.

Schreiner, H.R
Safe Ascent After Deep Dives,
Rev. Subaquat. Physiol. Hyperbar. Med. (in press, 1968)

Workman, R.D.
Calculation of Decompression Schedules for Nitrogen-Oxygen
and Helium-Oxygen Dives. Research Report 6-65. Washington:
U.S. Navy Experimental Diving Unit, 1965.

Final Report, Contract NAS 9-6978

Source Number of Illustrations

| Figure No. | Tonawanda Photography Department No. |
|---|---|
| 1 | 508-68 |
| 2 | 542-68 |
| 3 | 489-68 |
| 4 | 772-68 |